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Numerical modelling of POC yearly dynamics in the southern Baltic under variable scenarios of nutrients, light and temperature

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Abstract

This paper presents various scenarios of the particulate organic carbon (POC) in the southern Baltic Sea. The study is based on a one-dimensional Particulate Organic Carbon model (1-D POC). Mathematically, the pelagic variables of 1-D POC model are described by a second-order partial differential equations of the diffusion type with biogeochemical sources and sinks. The POC concentration is determined as the sum of phytoplankton, zooplankton and dead organic matter (detritus) concentrations. The temporal changes in the phytoplankton biomass are caused by primary production, mortality, grazing by zooplankton and sinking. The zooplankton biomass is affected by ingestion, excretion, faecal production, mortality, and carnivorous grazing. The changes in the pelagic detritus concentration are determined by input of: dead phytoplankton and zooplankton, natural mortality of predators, faecal pellets, and sinks: sedimentation, zooplankton grazing and biochemical decomposition.

The 1-D POC model was used to simulate temporal dynamics of POC in the southern Baltic Sea (Gdansk Deep, Bornholm Deep and Gotland Deep) under scenarios characterized by different temperature, nutrients and light. Daily, monthly, seasonal and annual variabilities of POC in the upper water layer are presented for the different scenarios. The starting-point of the numerical simulations was assumed as average values of the investigated pelagic variables for 1965–1998 period. Two- to three-fold increases of POC concentrations in late spring were revealed as well as the shift towards postponed maximum POC concentration. It is speculated that, due to POC increase, oxygenation of under-halocline water layer will decrease, while supply of food to organisms from higher trophic level should increase.

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1 Introduction

The high phytoplankton productivity in the Baltic (Hagström et al., 2001) makes it a key area on the European shelf as regards atmospheric CO_2 uptake (Thomas et al., 2003, 2005). Particulate organic matter (POM) is intermittent between inorganic carbon species and dissolved organic matter (DOM). DOM and POM play an important role in the carbon cycle as it is the largest organic carbon reservoir in the ocean (Packard et al., 2000). Moreover, dissolved organic matter determines a number of sea water properties, and processes occurring in the sea. These include direct and indirect influence on marine biota, complexation of heavy metals and nutrients, absorption of light in seawater and many others (e.g. Opsahl and Benner, 1997; Pempkowiak et al., 1984). The measure of both organic matter species is organic carbon: POC and DOC.

Both POC and DOC concentrations depend on the equilibrium between the sources and sinks of organic substances. When the rate at which organic substances are supplied increases, concentration of organic matter in seawater also increases until a new equilibrium is reached. Organic matter originates in a number of simultaneously occurring processes, e.g. primary production, biochemical degradation of organic detritus, extracellular release of organic compounds by biota – mainly phytoplankton, sloppy feeding by zooplankton and sediment resuspension (Chen and Wagnersky, 1993; Hygum et al., 1997; Nagata, 2000; Dzierzbicka-Glowacka et al., 2010).

Processes supplying organic matter to seawater are especially intensive in the coastal areas and land-locked seas. This is attributed to increased supply of nutrients from land that enhances primary productivity. As a result, both POC and DOC concentrations in the land locked seas e.g. the Baltic are 3–4 times higher than in the oceans (Kuliński and Pempkowiak, 2008; Grzybowski and Pempkowiak, 2003; Pempkowiak et al., 1984). Quantification of factors influencing both POC and DOC concentrations in seawater based on actual measurements is tedious due to natural variability of both POC and DOC concentrations (Kuliński and Pempkowiak, 2008; Grzybowski and Pempkowiak, 2003). Therefore experimental assessment of long time organic mat-

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ter changes in seawater is unrealistic, unless a several years long extensive survey is performed.

An obvious solution to the problem of assessing seasonal dynamics and long term organic matter concentrations changes is modelling. Moreover the modelling enables investigation of concentration dynamics caused by specific factors of environmental regimes (Kuliński et al., 2011; Dzierzbicka-Glowacka et al., 2010). Validation of results based on the comparison of the modelled and the measured POC concentrations in the Gdansk Deep, Baltic Sea, proved successful (Dzierzbicka et al., 2010). The developed POC model is based on a 1-D Coupled Ecosystem Model forced by 3-D hydrodynamical model and developed by Dzierzbicka-Glowacka (2005) and further parameterized by Kuliński et al. (2011).

One other advantage of the POC modelling is assessing changes that can be brought about by future regime shifts. The most certain regime shift that is being experienced in today's world is caused by the increasing atmospheric CO_2 concentration. The shift would influence, directly or indirectly, several factors important to organic matter levels in seawater. These include river run-off, river water nutrients and DOM concentrations, primary productivity, phytoplankton species composition and succession, seawater pH, and several others addressed as climate change. The impact of future climate changes on the physical conditions of the Baltic Sea and the dynamics of the deepwater inflows have been investigated in several studies (e.g. Meier 2006, Meier et al. 2006, BACC Author Team, 2008). Also biogeochemical models regarding the impact are available (e.g. Omstedt et al., 2009). However, so far, the impact of global change on the POC dynamics in the Baltic Sea has not been investigated and the response of the marine ecosystem to the expected changes is unknown.

In this manuscript an assessment of particulate organic matter concentrations yearly dynamics in the Baltic Proper seawater is presented. Contemporary POC concentrations are modelled under a variety of increased temperature and nutrients scenarios. Average values and increases of sea water nutrients concentrations, temperature and photosynthetically active radiation (PAR) observed in the period 1965–1998 (Renk,

2000) are used for assessing realistic environmental conditions in the years to come. The set of factors have been selected since they are considered as limiting for phytoplankton primary production and thus influencing POC concentrations directly and indirectly. Moreover, the rate of the factors increases have already been quantified based on actual observations (Renk, 2000). The study concerns scenarios for several areas of the southern Baltic Sea (Gdańsk Deep, Bornholm Deep and Gotland Deep).

2 Basic 1-D POC model concept

The biological part of 1-D CEM Coupled Ecosystem Model (Dzierzbicka-Glowacka, 2005, 2006) converted to a 1-D POC Particulate Organic Carbon Model with an equation for dead organic matter (pelagic detritus) is presented in Dzierzbicka-Glowacka et al. (2010) and Kuliński et al. (2011). The 1-D POC model is an ecosystem model able to simulate the particulate organic carbon (POC) concentration as the sum of pelagic detritus and both phytoplankton and zooplankton biomasses concentrations.

In this model nutrients are represented by two components: total inorganic nitrogen (NO_3^- + NO_2^- + NH_4^+) and phosphate (PO_4^{3-}). The temporal changes in the phytoplankton biomass are caused by primary production, excretion, mortality, grazing by zooplankton and sinking. The zooplankton biomass is affected by ingestion, excretion, faecal production, mortality, and carnivorous grazing. The changes in the pelagic detritus concentration are determined by input of: dead phytoplankton and zooplankton, natural mortality of predators, faecal pellets, and sinks: sedimentation, zooplankton grazing and decomposition (Dzierzbicka-Glowacka et al., 2010).

The zooplankton variable represents the zooplankton of the first order. They ingest both phytoplankton and pelagic detritus – dead organic material in the model. The closure term of the model system is the carnivorous grazing of the zooplankton. The way the closure term is formulated sets the behaviour of the model. The detritus pool is increased through faecal production of zooplankton and natural mortality of autotrophs and higher predators.

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The flow field and water temperature, as average values for the 1960-2000 period at investigated points, used as the inputs in the 1-D POC model, were reproduced by the 3-D hydrodynamical model IOPAS-POPCICE, which is now running for the period 1960–2000 (Osiński, 2008 and Project ECOOP IP WP 10, European COastal-shelf sea Operational observing and forecasting system integrated Project). The model was forced using daily-averaged reanalysis and operational atmospheric data (ERA-40) that were derived from the European Centre for Medium-range Weather Forecast (ECMWF). The interpolated output of the hydrodynamical model was used as the input in the 1-D POC model since, in the simulated areas, the dynamical characteristics remain almost unchanged in a horizontal plane in comparison to vertical changes. Hence, the magnitudes of the lateral import/export are lower, and the above assumption can be made.

3 Scenarios of future changes

The photosynthetically available radiation (PAR) at the sea surface I_o ($I_o(t) = \varepsilon Q_g$) is identified as ε ($\varepsilon = 0.465(1.195–0.195\,T_{\rm cl})$) where $T_{\rm cl}$ is the cloud transmittance function (Czyszek et al., 1979) of the net flux of short-wave radiation Q_g. The radiance $I_o(t)$ was expressed as a function of a daily dose of solar radiation η_d transmitted through sea surface using $\varepsilon{:}I_o(t) = \frac{\eta_d}{\lambda}\left(1+\cos\frac{2\pi t}{\lambda}\right)$ (λ is the length of day, in hours), where the average value of η_d for the southern Baltic Sea (for 1965–1998 period) was derived by means of the last squares method by Renk and Ochocki (1998).

Data from 34 past years (1965–1998) provide seasonal and annual variations of the water temperature and chlorophyll-a in the past and show the main trend of the parameters increase over the 4 past decades. The tendency of the average temperature increase in the surface water at the 0.006 °C year^{-1}, and in the upper layer by 0.0117 °C year^{-1}, was observed by the end of the period 1965–1998 (Renk, 2000). Moreover, an increase, by about 2% of average chlorophyll-*a* concentrations in the southern Baltic Sea in spring and summer was also observed. The average chlorophyll-

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a concentrations in the southern Baltic Sea (average values for 1965–1998 period) were used in this model for the calculation of primary production (Table 1). The 1-D POC model was used to simulate variations of the particulate organic carbon in the surface water layer (0–1 m depth) in the southern Baltic Sea. In the first step of our study, the calculations were made assuming the following:

1. increase in the water temperature in the upper layer: 0.008 °C per year,
2. increase in the available light: 0.2% per year in the vegetation season, and 0.05% in winter.
3. wind speed and direction as the average values for 1965–1998 period.
4. nutrients increase 1% of an average annual value per year.

4 Results

The starting-point of the numerical simulations was assumed as average values of the investigated pelagic variables for 1965–1998 period. Based on the trend indicated above, daily, monthly, seasonal and annual variabilities of primary production, phytoplankton, zooplankton, pelagic detritus and particulate organic carbon (POC) in different areas of the southern Baltic Sea (Gdańsk Deep – GdD, Bornholm Deep – BD and Gotland Deep – GtD) in the upper layer (0–10 m) were calculated for the different nutrients concentrations, available light, water temperature and wind speed scenarios.

As primary production is the basis for zooplankton and serves as both direct and indirect source of detritus, special attention is devoted to the characteristics of primary production in the study period. The seasonal variability of gross primary production in the southern Baltic Sea in a course of a year for the 1965–1998 period (average) and scenario for 2050 in the upper layer is presented in Fig. 1.

Seasonal dynamics of primary production in the upper layer in the study sites are characterized by two peaks; a sharp one during the spring bloom (ca. 12 mg C m^{-3} h^{-1}

in April – Gdańsk Deep, ca. 8 mg C m^{-3} h^{-1} in the second half of April – Gotland Deep and ca. 9 mg C m^{-3} h^{-1} at the turn of April and May – Bornholm Deep) and by the end of summer the other one, that is slightly higher than the first one in the upper layer (ca. 9 and 9.5 mg C m^{-3} h^{-1} in GtD and BD, respectively) for 1965–1998 period. The yearly trend of primary production in the surface layer in the Gdańsk Deep for 1965–1998 period also exhibits two characteristics peaks (Fig. 1): the first one during the spring bloom (the highest value – ca. 19.5 mg C m^{-3} h^{-1} in mid-April) and the second, a smaller one, in the late summer (ca. 13.5 mg C m^{-3} h^{-1}, a value close to the upper layer). In 2050, in the surface layer, the first maximum of primary production is some two times and the second maximum – 2.25 times higher as compared to the average 1965–1998.

Increase of primary production in scenario for 2050 as compared to the period 1965–1998 can be attributed to altered nutrients, temperature and radiation conditions (Dzierzbicka-Glowacka, 2005; Kuliński et al., 2011). Typical features of primary production seasonal dynamics are well reflected in the annual primary production cycles. In particular, a well developed spring bloom (April), and somehow less intensive, but prolonged late summer/autumn bloom (August and September) can be clearly distinguished. The curve representing primary production integrated over the whole upper water layer exhibits a slightly less intensive spring peak in BD and GtD (Fig. 1), obviously due to limited primary production in the subsurface water layer. There are small differences between curves characterizing primary production in GdD in the surface and the upper water layer in autumn, due to more intensive mixing of water.

Time series scenarios of the state variables *Phyt*, *Zoop*, *DetrP* and *POC* are presented in Fig. 2. (Gdańsk Deep, surface layer) and Fig. 3 (Gdańsk Deep, upper layer), while simulated monthly and seasonal averages for phytoplankton, zooplankton, pelagic detritus and POC in the all three areas (GdD, BoD, GtD) for the 1965–1998 period and 2050 are presented in Figs. 4 and 5.

In the surface layer of the Gdańsk Deep in 1965–1998 (Fig. 2a) a strong increase of phytoplankton biomass, up to 380 mg C m^{-3} in April is observed. It is due to bioavail-

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ability of nutrients and light in this time. After the spring bloom there is a distinct decrease of phytoplankton biomass down to 140 mg C m^{-3}. The considerable increase of zooplankton is observed at the beginning of summer in June (ca. 150 mg C m^{-3}) related to large pelagic biomass and phytoplankton spring growth – the base of zooplankton food. Pelagic detritus concentration is characterized by one strong maximum in mid-May reaching over 400 mg C m^{-3}. It results from mortality of phytoplankton after spring bloom. Particulate organic carbon reaches the highest value during spring with the distinct maximum in April – ca. 590 mg C m^{-3}. In June a decrease in POC to ca. 350 mg C m^{-3} is observed. At the end of a year (in December) concentration of POC decreases considerably, down to 90 mg C m^{-3} .

In the upper layer of the Gdańsk Deep in 1968–1998 (Fig. 3), increase and decrease of phytoplankton, zooplankton, detritus and POC occur, but their first-spring concentrations maxima are lower: 200 mg C m^{-3} for phytoplankton biomass in April, 110 mg C m^{-3} for zooplankton in June and 360 mg C m^{-3} for pelagic detritus at the end of May.

Concentration of POC reaches about 410 mg C m^{-3} in the upper layer from April to November. The concentrations of POC in scenario for 2050 are twice of these characteristic of scenario for 2010 and are 2,5 fold larger than that in the period 1965–1998.

The annual cycles of POC and contributing factors: phytoplankton (*Phyt*), zooplankton (*Zoop*), and detritus (*DetrP*), both in the whole upper water layer (Fig. 3) and in the surface layer (Fig. 2.) indicate large POC concentrations in early summer resulting from the *Phyt* bloom and detritus originating from *Phyt* mortality. Zooplankton contributes little, if anything, to the POC pool up till the late June. Between July and November zooplankton is the least of the three POC components. The *Phyt* contribution to POC is close to the detritus contribution. One specific feature of the *Phyt* cycle presented in Fig. 2, as compared to the primary productivity (Fig. 1), is much lower biomass in the second half of the year. This is caused by *Phyt* decrease due to mortality and *Zoop* grazing. Larger concentrations of POC calculated for the successive decades reflects increased primary production in 2010 as compared to the average in the period 1965–1998. This, of course, leads to larger *DetrP* and *Zoop* concentrations; both contributing to POC. The POC increase is even more pronounced. An interesting shift in the cycles can be noticed towards 2050. A large peak of zooplankton develops in October. This leads to a fast decrease of phytoplankton and detritus in October and November. However, zooplankton gaining importance as a component of POC, leads to extended POC concentration peak between August and early October. As a consequence concentration of POC in the range between 900 and 1000 mg m^{-3} persists between April and October with, just, a three weeks long brake in July.

Changes in the POC annual cycle are even easier to spot when concentrations, in the upper water layer, are considered (Fig. 3). In 2050 a pronounced POC peak develops already early in August, lasting though August and September. This can be attributed of limited grazing by zooplankton and large concentrations of phytoplankton and detritus. The period of late August and September witnesses the maximum POC concentration due to increased concentrations of zooplankton. This is followed by a rapid POC decrease caused by zooplankton grazing on detritus and phytoplankton, and decline of primary production in November due to decreasing temperature and light.

The cycles of POC itself and POC components look differently in the Bornholm Deep (Fig. 4). For one thing POC levels are lower, due to lower primary productions caused by limited supply of nutrients (Renk, 2000). Then zooplankton never develops as major component of POC. Therefore both *Phyt* and *DetrP* concentrations decrease slowly in the autumn. This leads to a gradual decrease of POC concentration by 25% in September/October, and by 20% in October/November. Still another POC cycle characterizes the Gotland Deep. Primary productivity peak begins in April/May. There is no zooplankton that might modify *Phyt* and *DetrP*. Therefore the POC is composed of *Phyt* and *DetrP*, the latter derived from phytoplankton. There is just one peak of POC. It occurs in June, 1965-1998 and in July 2050. Due to slow development of zooplankton in August and September (both 1965-1998 and 2050), phytoplankton and detritus

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decrease slowly leading to gradual decrease of POC.

The varying patterns and levels of POC in the three deeps considered can be best seen in Figs. 4 and 5 where monthly and seasonal averages of the POC are presented. In the Gdańsk Deep increased POC concentrations from 400 mg C m^{-3} (2010) to 900 mg C m^{-3} (2050) in spring are evident. Moreover, monthly averages for August and September, 2050 exceed these of April and May, 2050 whereas in the period 1965–1998 averages for August and September are lower than these for April and May by some 25%. The other difference of the pattern – increased contribution of the zooplankton biomass to POC in August and September is also evident (Fig. 2). The development of zooplankton causes still another effect – a rapid decrease of POC concentrations. Concentrations of POC decrease rapidly. In November, 2050 POC decreases by 50% while in November, 1965–1998 by just 20%. The difference is caused by rapid decline of *Phyt* and *DetrP*, both due to feeding of zooplankton on both of the other POC components. Increased temperature and light contribute to the prolonged growing season in 2050.

The highest increase in seasonal averages of the investigated variables in the surface layer of the Gdańsk Deep take place in spring (in April) for phytoplankton (ca. 141%), in autumn (in October) for zooplankton (ca. 360%), in spring (in May) for pelagic detritus (145%), in summer (in September) for POC (ca. 131%). However, the highest increase in seasonal averages of the pelagic variables in the upper layer of the investigated areas takes place: in spring and summer for phytoplankton, in autumn for zooplankton, in summer for pelagic detritus and POC; i.e. (a) in the Gdańsk Deep: for phytoplankton (ca. 145% and 138%), for zooplankton (ca. 267%), for pelagic detritus (ca. 101%) and POC (ca. 123%); (b) in the Bornholm Deep: for phytoplankton (ca. 152% and 143%), for zooplankton (ca. 192%), for pelagic detritus (ca. 104%) and POC (ca. 111%); (c) in the Gotland Deep: for phytoplankton (ca. 138% and 161%), for zooplankton (ca. 153%), for pelagic detritus (ca. 125%) and POC (ca. 108%).

It is interesting to notice that the POC increase slows down as the time elapses. This is documented by the average relative yearly POC increases (Fig. 6) calculated as the

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decadal increases.

Percentage contributions of the POC components in the upper layer of the study sites for the 1965–1998 period, 2010, 2020, 2030, 2040 and 2050, the year average (Fig. 7a) and at 285th day of the year (Fig. 7b) are presented. The increasing contribution of zooplankton in POC, over decades is evident for the GdD. The contribution is similar and constant in the GtD and BD (Fig. 7a). This supports the overview of results presented earlier. Percentage contribution of yearly, averages of the POC components is also presented (Fig. 7b). Contribution of phytoplankton in POC increases by 10%, 5% and 2% causing thus a decrease in pelagic detritus by 8%, 5% and 2% in GtD, BD and GdD, respectively. Participation of zooplankton in POC increases by 5% in GdD, only; however, in GtD, it decreases by 2% and in BD, it is constant over time.

5 Discussion

Primary productivity and POC concentrations calculated for the period 1965–1998 and 2010 agree well with experimental data. Both actual concentrations and major features of seasonal changes are well reflected on the annual curves (Dzierzbicka-Glowacka et al., 2010; Pempkowiak et al., 1984). The increase in *Phyt*, *Zoop*, *DetrP*, and POC concentrations caused by the increased nutrients supply and favourable light and temperature is also well captured when the 2010 data are compared to the average of 1965-1998 (Figs 2-5). Therefore it can be safely assumed that the calculated data reflect sufficiently well the POC variations in the Southern Baltic, caused by the increase of nutrients, PAR and temperature.

The increased POC will have contradictory effects on the Baltic ecosystem. On the one hand it means increase base of the food pyramid (Raymont, 1976.) and concentrations decrease of contaminants in particulate organic matter (Pohl et al.,1998; Pempkowiak et al., 2006). Both the factors will influence the ecosystem in a favourable way. This might have important consequences for the Baltic fishery as the increased supply of zooplankton will constitute base for development of the southern Baltic fish stocks.

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On the other hand the increased supply of POC will lead to increased load of fresh organic matter sinking below the halocline. This suggests an intensified organic matter supply to bottom sediments and possible ecological consequences due to further oxygen depletion in the below the halocline water layer and in the bottom sediments. The feature will have a negative effect on the ecosystem (Voipio, 1981). Moreover, considering the extent of anoxic zones in the Baltic in the nineteen ninety's (HELCOM, 1996) caused by primary production in the period 1965-1998, and its increase in 2050 (Table 1), it can be concluded that the situation will worsen considerably.

There are very few other factors that influence POC concentrations that are not considered in our simulations. These include organic matter originating from resuspended sediments, and organic matter discharged with the river run-off (Pempkowiak and Kupryszewski, 1980; Pempkowiak, 1985; Petterson et al., 1997; Pocklington and Pempkowiak, 1984). These are certain to have minor effects on POC concentrations in the 'open' Baltic, as far as loads of particulate organic matter are considered. Increasing concentrations of carbon dioxide in the atmosphere is yet another factor not considered in the simulations. This is certain to cause both acidification of sea-water and increased primary productivity (Omstedt et al., 2009; Caldeira and Wicket, 2003; Tortell et al., 2006). Therefore this may be yet another factor influencing POC concentrations due to primary productivity shifts. The acidification expected to take place till 2050 may be insufficient, however, to affect primary productivity (species and species succession) substantially.

Of course the actual nutrients, light, and temperature levels may differ from the ones assumed in our simulations. Still our results indicate clearly and in the quantitative way the sort of changes in the POC concentrations in the Baltic sea-water that may be expected in the forthcoming few decades.

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6 Conclusions

According to the simulated data, for daily, monthly, seasonal and annual variability of POC for the assumed nutrients concentrations, available light, water temperature and wind speed scenarios, the increase in annual average of the POC concentration in the southern Baltic Sea is expected (see Fig. 4 and Table 2), i.e. for phytoplankton – ca. 110%, for pelagic detritus – ca. 63%, POC – ca. 72.5% (90% in Gdańsk Deep) and for zooplankton ca. 50% and 75% in Gotland Deep and Bornholm Deep, respectively; except the Gdańsk Deep, where the increase is considerable, ca. 130%. This situation is caused by the occurrence of a large zooplankton biomass in fall (ca. 380 mg C m^{-3} in the second half of October) which is the result of the high phytoplankton biomass (ca. 370 mg C m^{-3}) and pelagic detritus concentration (ca. 380 mg C m^{-3}) throughout the summer.

The increase in primary production and phytoplankton biomass causes the increase in zooplankton biomass and pelagic detritus concentrations and the increase of zooplankton consumers biomass including fish. Received results for assumed scenarios bear important consequences for the Baltic ecosystem. Excess particulate organic matter sinks on the bottom, where it is mineralized, causing loss of oxygen in the below the halocline water layer. Thus the increased primary production will contribute to more frequent and intense oxygen depletion events in the benthic waters and occurrence of hydrogen sulphide there.

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Table 1. Average chlorophyll *a* concentration in the upper layer in the southern Baltic Sea (average values over the 1965–1998 period), Renk (2000).

period	chlorophyll-a (mg m^{-3})		
	Gdańsk	Bornholm	Gotland
1–10 January	0,56	0,60	0,45
11–20 January	0,48	0,59	0,50
21–31 January	0,40	0,60	0,53
1–10 February	0,41	0,51	1,09
11–20 February	0,48	0,50	0,55
21–28 February	0,55	0,47	1,13
1–10 March	0,55	0,76	1,26
11–20 March	1,14	0,62	1,62
21–31 March	1,58	1,08	3,63
1–10 April	5,39	0,94	3,01
11–20 April	4,99	2,79	1,45
21–30 April	5,35	3,39	2,81
1–10 May	2,11	3,57	2,46
11–20 May	2,80	1,64	2,22
21–31 May	3,04	1,60	1,76
1–10 June	2,20	1,42	2,06
11–20 June	1,97	1,83	2,07
21–30 June	1,71	1,42	2,34
1–10 July	2,10	1,42	2,16
11–20 July	2,34	1,70	1,86
21-31 July	2,71	1,53	2,18
1–10 August	2,56	1,92	1,86
11–20 August	2,42	2,26	2,48
21–31 August	2,46	2,04	2,14
1–10 September	3,01	1,61	2,26
11–20 September	2,55	2,57	3,15
21–30 September	3,62	2,06	2,29
1–10 October	2,88	2,09	2,85
11–20 October	2,06	2,46	3,22
21–31 October	4,68	1,78	1,69
1–10 November	5,76	4,21	1,83
11–20 November	3,63	4,28	1,04
21–30 November	1,86	2,11	
1–10 December	2,18	2,69	
11–20 December	1,19	2,14	

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Table 2. The simulated annual averages the investigated variables in the upper layer in 1965–1998 period and 2050.

Region	Variables	1965–1998	2050	Increase
Gdańsk Deep:	phytoplankton	88 mg C m^{-3}	180 mg C m^{-3}	105%
	zooplankton	49 mg C m^{-3}	115 mg C m^{-3}	130%
	pelagic detritus	135 mg C m^{-3}	221 mg C m^{-3}	64%
	POC	272 mg C m^{-3}	516 mg C m^{-3}	90%
Bornholm Deep:	phytoplankton	69 mg C m^{-3}	141 mg C m^{-3}	104%
	zooplankton	24 mg C m^{-3}	42 mg C m^{-3}	75%
	pelagic detritus	115 mg C m^{-3}	180 mg C m^{-3}	57%
	POC	210 mg C m^{-3}	364 mg C m^{-3}	73%
Gotland Deep:	phytoplankton	70 mg C m^{-3}	155 mg C m^{-3}	121%
	zooplankton	30 mg C m^{-3}	45 mg C m^{-3}	50%
	pelagic detritus	123 mg C m^{-3}	203 mg C m^{-3}	65%
	POC	230 mg C m^{-3}	395 mg C m^{-3}	72%

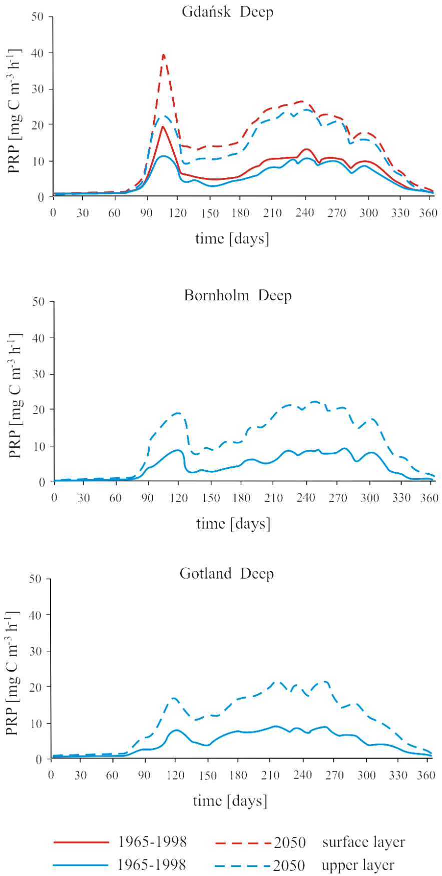

Fig. 1. Simulated annual cycles for primary production (midday values) in the upper layer of the Gdańsk Deep, Bornholm Deep and Gotland Deep for the 1965–1998 period and 2050.

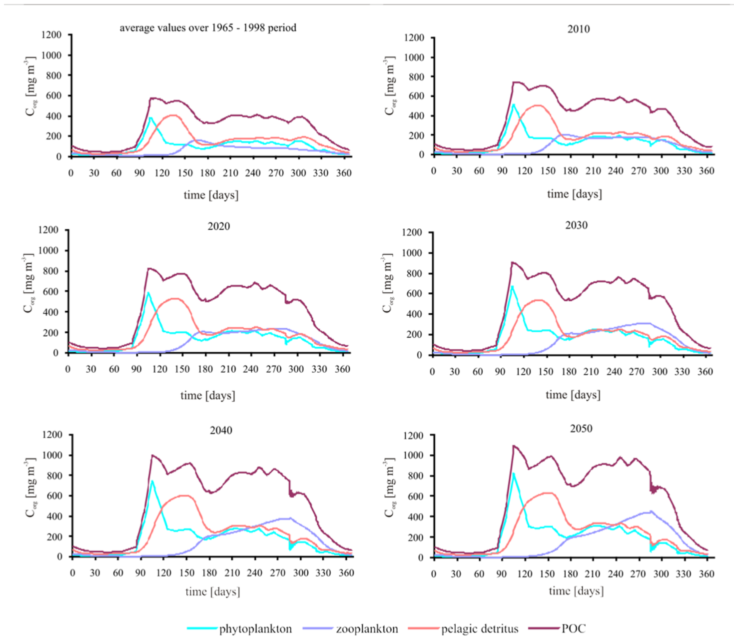

Fig. 2. Simulated annual cycles for phytoplankton, zooplankton, pelagic detritus and POC in the surface layer of the Gdańsk Deep for the 1965–1998 period, 2010, 2020, 2030, 2040 and 2050.

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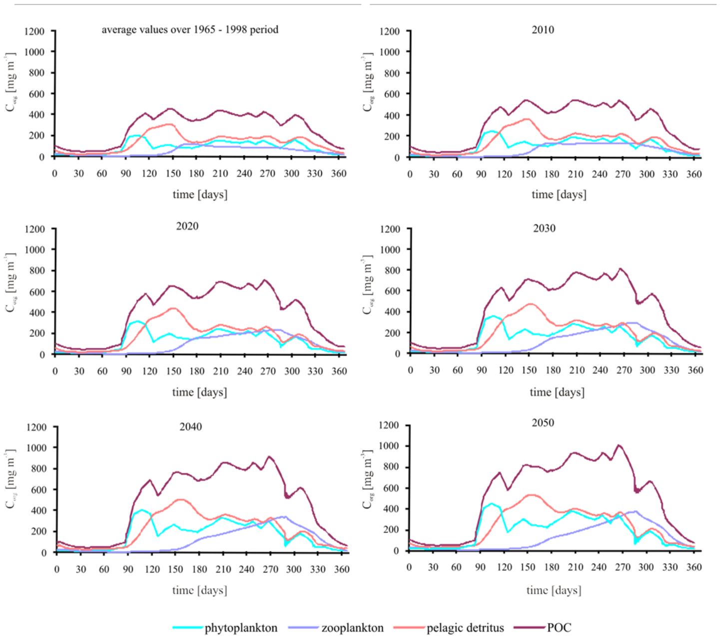

Fig. 3. Simulated annual cycles for phytoplankton, zooplankton, pelagic detritus and POC in the upper layer of the Gdańsk Deep for the 1965–1998 period, 2010, 2020, 2030, 2040 and 2050.

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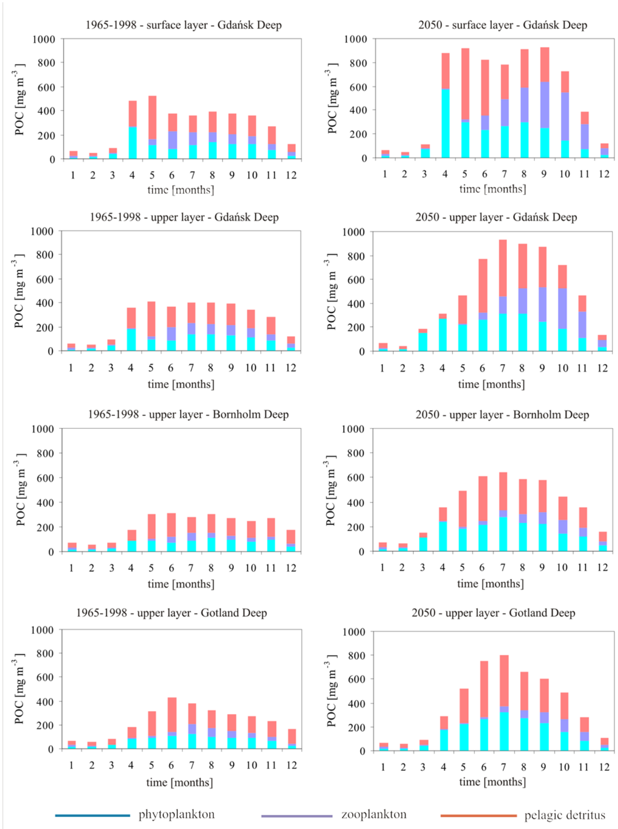

Fig. 4. Simulated monthly averages for phytoplankton, zooplankton, pelagic detritus and POC in the surface/upper layer of the Gdańsk Deep and in the upper layer Bornholm Deep and Gotland Deep for the 1965–1998 period and 2050.

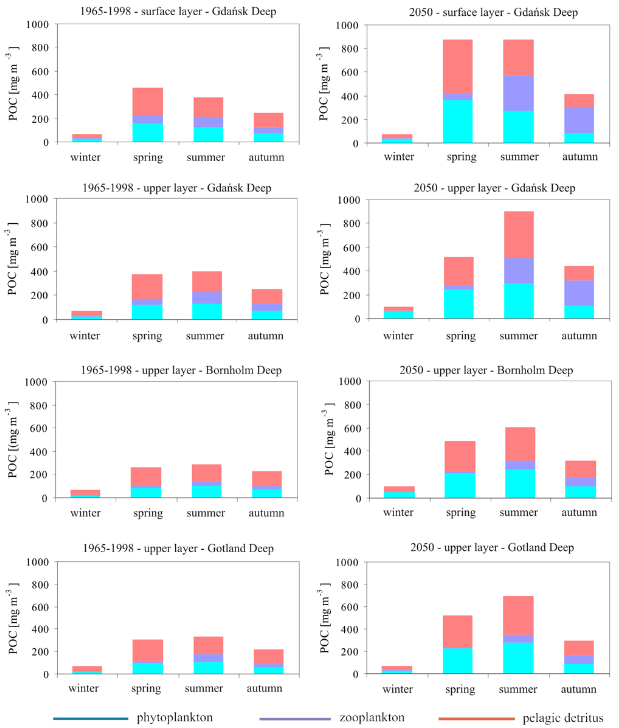

Fig. 5. Simulated seasonal averages for phytoplankton, zooplankton, pelagic detritus and POC in the surface/upper layer of the Gdańsk Deep and in the upper layer Bornholm Deep and Gotland Deep for the 1965–1998 period and 2050.

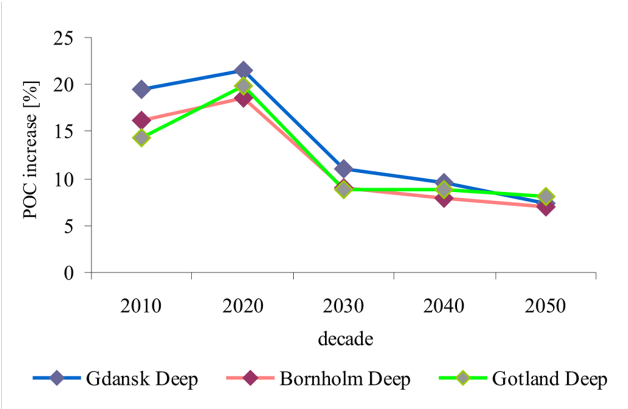

Fig. 6. Simulated POC increase in the upper layer of the Gdańsk Deep, Bornholm Deep and Gotland Deep with relation to preceding decade.

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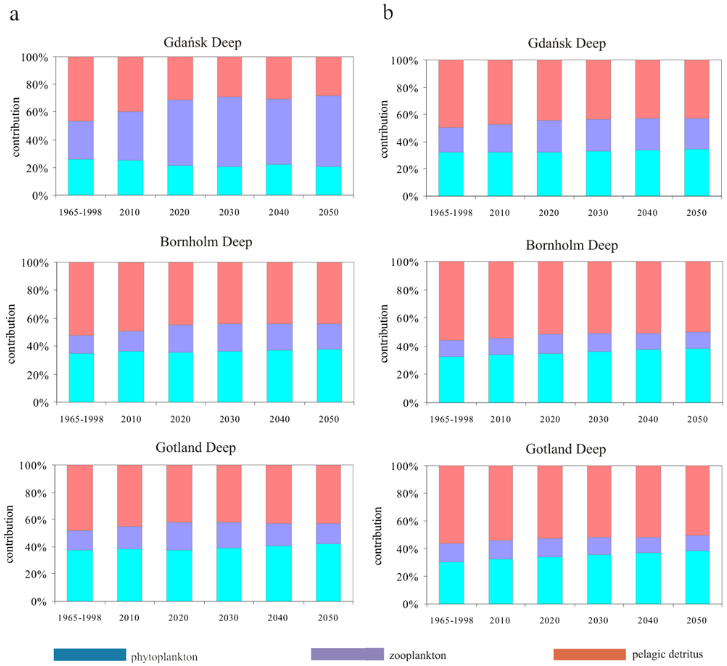

Fig. 7. Percentage contributions of the POC components in the upper layer of the study sites for the 1965–1998 period, 2010, 2020, 2030, 2040 and 2050, the year average **(a)** and at 285th day of the year **(b)**.